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Development of a Hydrogen Fuelling Infrastructure in the Northeast United States

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Executive Summary

The project proposes the implementation of a hydrogen refuelling infrastructure for the Northeast U.S., including major population hubs Boston, New York City, Philadelphia and Washington D.C. A development timeline plan is presented from 2013-2025 for the construction of a hydrogen refuelling and production network. The timeline was broken down into three sections, phase I (2013-2015), phase II (2015-2020) and phase III (2020-2025).

Development of critical selection criteria was undertaken, selecting locations for possible refuelling stations depending on population density, demographics and traffic density. This identified suitable locations for the initial installations of refuelling stations when the first hydrogen fuel cell vehicles became commercially available. This was continued through the three time phases to implement an expanding network of refuelling stations to service demand and ensure consumer convenience.

As well as identifying refuelling station locations, sourcing of hydrogen which will supply these stations was investigated. The technologies selected for hydrogen production were; steam methane reforming, water electrolysis, and coal or biomass gasification. Existing natural gas, coal and biomass infrastructures were considered for hydrogen generation and supply; with additional large wind farms could represent production of hydrogen during off peak hours when electricity demand is low and therefore the price is at its lowest, making it economically attractive.

After the identification of possible locations for refuelling stations, the sizing of these stations and the timing of their construction was determined. Phase I introduces a skeleton network across metropolitan areas and major roadways. Before expansion into targeted areas to exploit early adopter markets in phase II, instigating penetration of hydrogen fuel into the transportation market. Phase III brings consumer convenience before, ultimately, developing a free-market hydrogen economy across the Northeast U.S.

A vital parameter for the construction of a hydrogen fuel cell refuelling network is the cost to the consumer. For the uptake of fuel cell vehicles, the cost of hydrogen fuel cell vehicles, and thus hydrogen itself, must be economically comparable with existing gasoline vehicles. At the same time the cost to build the refuelling network must represent a suitable investment opportunity and the consequent cost of hydrogen paid by the consumer must be profitable in the long term.

The planned infrastructure implementation has an overall capital investment of $5.5 billion from 2013-2025 and a price of $6.75 per kilogram of hydrogen throughout the project timeline, this represents a comparable price to the existing price of gasoline equivalent. Using this pricing strategy the cashflow shows profitability in 2031 and breaks even in 2040.

The codes, regulations and standards for the implementation of a hydrogen refuelling network have been vigorously consulted and planned infrastructure has been modified to comply with these. A progressive marketing campaign has been planned to coordinate safety education and drive demand through increased public awareness and allaying fear.
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1. Criteria Development

In order to locate the positions, number and type of refuelling stations to form a hydrogen networks criteria need to be developed in order to provide a selections process. These criteria and the weighting they are given will change and evolve through the different phases, and often within a phase there are different criteria relating to priorities and numbers of station falling under each priority.

1.1 Criteria for Selection and Justification

The main criteria need to be identified and given priority during the different phases of development. The following sections identify key criteria that must be assessed in order to achieve a functional, cost-effective and efficient role out of a hydrogen infrastructure.

1.1.1 Traffic Density

Traffic density can provide a pivotal piece of information in assessing the locations of individual refuelling station or routes that should be developed. However, in assessing the development of the network it provides information on the end-goal of the project during phase III and when combined with information such as population density and income distribution for phase II. It is vital that key routes are identified and supplied with refuelling access, traffic density data is one of the best methods identify these routes.

1.1.2 Population Density

Another important factor for the use of hydrogen vehicles is population density. With an estimated 300,000 vehicles in use by 2030, facilitating and refuelling these vehicles leads to a need to identify where they are to be kept. In addition there is a need to provide for convenient consumerism during the later phases of network development which includes positioning locations within a certain distance of the majority of consumer’s place of residence.

1.1.3 Land Cost & Income Distribution

Another factor to consider is exactly how much of the local population would be able to purchase and use a hydrogen vehicle. Even with the level of market penetration that is anticipated, fuel cell cars would still be expensive and only available to certain tiers of consumers. As such, it would be beneficial to have a higher number of stations in the areas that are most affluent and therefore, would have greater access to HFCVs. So when looking at this criteria, both local land price and local income distribution is important to identifying key locations. In addition the cost of purchasing land, or leasing land for the construction of hydrogen refuelling stations is an important factor in determining the cost benefit analysis of each station.

1.1.4 Geographical Demands

When considering potential fuel station locations local geographical demands must be considered. This can be broken down into several components. Firstly, it is of paramount importance to ensure an even spread of stations across a given area/route as possible. Secondly, it is important to study existing gasoline/diesel/LPG stations to look for opportunities in retrofitting existing stations and thirdly, to consider local opportunities for supplying hydrogen.
1.1.5 Marketing, Outreach and research facilitation

The need to facilitate marketing, outreach and research during network development has an interesting effect on the placement of locations, especially during the early phase of the network development. Not only is there a need for marketing, outreach and research to instigate awareness, increase demand and reduce costs but also areas which welcome these projects are likely to help facilitate the construction of sites and use them as they develop. This makes locating these areas important as they provide benefits to certain locations. In addition it is important to know existing projects as not to interfere with their on-going deliverables but also as to not repeat previous work.

1.1.6 Hydrogen Costs

As mentioned under geographical demands above each location is subject to a fluctuation in the price of hydrogen, whether that be because of logistical considerations or due to the methods of production that best suits the local area. In either case the cost at which hydrogen can be supplied at a given location is an important factor to the viability of a given location.

1.2 Weighting of Criteria

During the development of the network the weighting of each criteria (and in some cases additional criteria) will evolve. As such, it is outlined below, how in this project the weightings have been given during each phase of network development.

1.2.1 Phase I: Minimum Required for Initial Travel

The weighting criteria during Phase I should be focused on the geographical locations of the stations with the aim of completing a skeleton network which facilitates a journey from Boston to Washington creating the opportunity to enhance research, outreach and educational programs.

During Phase I there will be relatively few cars. The initial Phase will also be focused on consumer awareness and publicity. The creation of a hydrogen highway is a good publicity focused goal; it will make a hydrogen network seem a viable alternative to conventional fuel. The exact locations of the refuelling points should be situated to facilitate research or to enhance outreach and educational projects, reducing costs through research and stimulating demand through outreach and marketing. This leads to two main criteria for choosing locations during phase I: criteria 1 being the suggestion of locations that facilitate a complete journey between Washington and Boston; criteria 2 being the exact location of sites, located as such to enhance research or marketing projects.

In addition the priority of locations suggested can be split into two tiers. Tier 1 represents essential locations chosen to make sure a journey is possible, based on a geographical assessment on the ranges of fuel cell vehicles. Tiers 2 and 3 are the optimum locations and number of stations chosen to be placed within 50 miles of each other to alleviate the concern of consumers ‘range anxiety’.

1.2.2 Phase II: Targeted Deployment for Early Markets

Phase II sees the need to expand the hydrogen refuelling infrastructure from the minimum required for a network between Boston and Washington to a targeted distribution of refuelling sites across the Northeast seaboard. This sees the weighting of the criteria for selection move from a bias towards pure geographic consideration to a bias towards facilitating the demand of the early
adopter markets. The main criteria bias in this instance is towards traffic density, income distribution and location of fleet bases.

As with Phase I the priority of locations can be sorted into tiers representing the importance of the location. In each tier the criteria for selection represents the shift mentioned above. Tier 1 represents the essential locations that must be established within the first stages of phase II. These sites are the sites identified under phase I’s optimum scenario but are essential to establishing a consumer friendly Hydrogen network. Tier 2 includes the locations with second highest priority. The number of stations under tier 2 represents the minimum number required to service demand. As such these are still mostly geographical chosen locations filling the gaps remaining from tier 1 and with heaviest weighting given to areas of high income distribution and the location of possible fleet basis. Tier 3 locations are the locations of least priority of phase II, the number of stations represents the chosen optimum number at the end of 2020. The criteria of location selection has shifted from necessity to facilitating demand, with focus given to areas of high traffic density, high income distribution and the use by possible fleet bases.

1.2.3 Phase III: Convenient Consumerism

By 2020, a sufficient placement and distribution of hydrogen refuelling stations will be located through the Northeast United States. Thus the question is a matter of meeting the increasing demand and variability in locations with an improved cost effectiveness of operation. Having 7 years’ experience in installation and operation of hydrogen refuelling stations, the best way to increase effectiveness is to ensure maximum potential output through population density information, alongside cheap land cost for any potential new refuelling stations. This would hopefully allow customers the same level of convenience in terms of refuelling as they currently experience with their current gasoline vehicles.

The exact location chosen can be separated within three tiers of priority with a shift in weight of criteria between them. Tier 1 represents the station locations chosen under tier 3 of phase II. These are seen as a priority under Phase III in establishing a convenient infrastructure for the early adopters to use. As the fuel cell vehicle moves away from the early adopter market into the consumer mainstream it leads to tiers 2 and 3 of phase III. Tier 2 stations are noted as the minimum to provide a convenient refuelling network across the Northeast seaboard. The number of stations is the minimum required to facilitate the convenient use by early mainstream consumers. As such the criteria of selection focuses on population and traffic density information as well as the economic input of the cost of supply of hydrogen. Tier 3 represents the optimum number of stations to provide a convenient and easy to use hydrogen infrastructure to the early mass market. The criteria for choosing the additional locations focuses on the economics of supply and demand; tying population density, traffic density with the cost of supply and land pricing.

1.2.4 Phase IV: Free Market Economics

Whilst not included in the scope of the project, Phase IV is seen as the point where free market economics will take over from necessity in entirety when considering hydrogen infrastructure. This is also the stage at which it is anticipated that government incentives for a hydrogen infrastructure can start to be withdrawn. If projected car sales move the way suggested in the guidance documents, there will be a daily demand for 600 metric tons of hydrogen in the Northeast region of the U.S. alone. This demand will match the supply of 1000 mid-sized (150 kg) filling stations. As growth expands after 2025 this demand will only increase, and hydrogen will become as ubiquitous as
gasoline and profitability rather than incentives will determine the location of hydrogen filling stations.

2. Hydrogen Refuelling, Transportation and Production

This section considers the current technology available for hydrogen refuelling and transportation and the implications this has for the design, development and roll out of a hydrogen infrastructure. It forms a baseline for evaluation and the planned development of the network.

2.1 Refuelling Stations

Data provided estimated that there will be 1 million hydrogen vehicles present in the U.S. and 300,000 will be in the Northeast region by 2020. Based on calculations from average fuel consumption and driving distances (4), a hydrogen requirement of 0.5kg/day per vehicle has been assumed. Processing this level of demand, a minimum supply level of 150,000 kg of hydrogen per day for 2020 is estimated. To predict the hydrogen use up to 2025 U.S. Department of Energy (DOE) predictions have been used. The U.S. DOE (1) has 4 scenarios predicting the number of hydrogen vehicles on the road in the U.S. up to 2025. In our work we have assumed that 1 in 6 of the cars to be sold in the U.S. are sold in the northeast region. These cars are expected to require an average of 0.5kg of hydrogen per day, Figure 1. This shows that by 2025 there is expected to be between 300,000 and 1.7 million hydrogen vehicles which will require between 150 and 850 tons of hydrogen per day.

![Figure 1 - Projected Fuel Cell Vehicle & Hydrogen Requirement for Northeast U.S.](image)

2.1.1 Technology Available

Hydrogen refuelling stations are becoming commercially available with a variety of products offered. The main differences between commercially available products are whether the station relies on off-site or onsite hydrogen generation. Stations utilising on-site hydrogen production either reform hydro-carbon products or perform electrolysis of water. In either case the stations need supplying with a feedstock, e.g. biomass, methane or water and electricity. Stations relying on external supplies of hydrogen either through canisters or piped hydrogen need to be located within a supply chain or distribution infrastructure.
In general refuelling stations require ancillary equipment, e.g. compressors to meet the demand of refuelling a hydrogen car. Currently refuelling nozzles are standardised and the stations need to be capable of delivering 35MPa or 70MPa of hydrogen with 70MPa becoming the more common standard. There are some limitations on the design of a station with respect to the positioning of hydrogen this is covered in more detail in the Code and Regulations section and affects location evaluation.

2.1.2 Capacity

Existing hydrogen fuelling stations have a vast discrepancy in delivery capacity. UC Irvine’s 3rd generation fuelling station has on-site storage of only 25kg per day, up to 50kg max, which wouldn’t be capable of providing more than a full refill to ~15 vehicles. However recent newer stations such as examples in Hamburg (2012) are capable of delivering 750 kg/day (6) of hydrogen. In this work we have specified 4 different types of station. Portable (100kg/day), small (250kg/day), medium (400kg/day), and a large station (1000kg/day).

2.1.3 User Number

Based on calculations the proposed minimum of 300,000 fuel cell vehicles be on roads by 2020, would require ~150,000 kg/day. The upper and lower limit of number of fuelling stations is 1500 (based on a 100 kg/day fuelling station) to 150 stations (based on a 1000kg capacity). For the basis of this report the minimum figure has been used to provide approximate numbers needed within each defined area of the Northeast seaboard.

2.1.4 Types of Refuelling Station

2.1.4.1 Semi-Permanent Refuelling Stations:

Semi-permanent hydrogen refuelling stations can produce around 50-100kg of hydrogen a day, which is enough to fill 10-20 cars a day. These are often built in standard size ISO 20ft containers, and are expandable by adding extra units. This makes them very attractive for early stage implementation. There are limits to the number of users for each station and the number required to meet the demand at later stages would be prohibitive. Hydrogen can either be produced on site by electrolysis, or trucked to the station, the trailer is often used as the onsite hydrogen storage and swapped with a full one when required. These stations have been chosen for the initial stages of infrastructure, as they are quick to build and can be moved as the infrastructure grows. We will use portable stations to create an instant skeleton network while permanent stations are being built.

Figure 2 – (a) ITM Power semi-permanent refuelling station (2), (b) Shell hydrogen refuelling station in Los Angeles (3)
2.1.4.2 Permanent Refuelling Stations:

These are like traditional gas stations, the hydrogen can either be produced on- or off-site. These take much longer to plan and build and the capital costs for a permanent station are much higher than for semi-permanent stations. However these stations are capable of reaching much higher capacities than portable stations. We have planned the stations with the ability of expanding smaller stations into larger stations which will cost half of the build cost for the larger station. While the costs of building a smaller station and upgrading it will be greater in the long term than oversizing a station initially the upgrading will spread the costs over a greater time scale, and allow more stations to be built quicker to cope with demand. A permanent station can have on or off site hydrogen production. On site hydrogen production could be by electrolysis or SMR, while hydrogen can be delivered by truck or pipeline.

2.2 Hydrogen Transportation

The capabilities of the different techniques for distributing hydrogen have a large impact on the methods suggested for producing hydrogen and in the strategic placement of some refuelling sites. When considering hydrogen transportation it must be noted that for some refuelling sites, onsite generation of hydrogen may be preferential to off-site generation. This might be the case when considering locations local to municipal waste site, areas of large biomass production, or where the delivery of hydrogen is impractical. In these cases different goods often need to be transported to and from sites. However in this section of the report only the transportation of hydrogen and the implications this has on refuelling locations is considered. There are 3 main hydrogen transport mechanisms; gaseous trucked, gaseous piped, and liquid trucked. In this report only gaseous transport has been discussed as the energy cost of liquefaction is very high, Compressing hydrogen to 30 MPa or 70 MPa requires 1.05 or 1.36 kWh/kg H₂ respectively, whereas cryogenic hydrogen storage requires 10-13 kWh/kg H₂.(4).Methods

2.2.1.1 Transporting Compressed Gas Hydrogen by Truck

The transportation of hydrogen in the form of compressed gas canisters is by far the most commercially exploited so far. The exact costing of this delivery method is dependent on the nature of freight (road, rail or ship) and the length of the journey. Delivering hydrogen by truck is limited by the size of the trucks. Up to 250kg of hydrogen can be delivered in the largest hydrogen trucks which means that unless multiple refuelling’s per day are required for medium and large stations and it has been assumed that these can’t be refuelled by truck. It is also unfeasible to deliver hydrogen over 200km by hydrogen truck. This presents significant hurdles to the strategic roll out of a hydrogen infrastructure.

2.2.1.2 Transporting Compressed Gas Hydrogen by Pipe

The transportation of hydrogen via pipe has been touted as a long term goal in establishing the hydrogen economy. Several locations already operate with piped hydrogen as the feed for refuelling stations, such as the southern California example. The similarities between piped hydrogen and already established networks such as natural gas and long established engineering principles in the area through extensive chemical engineering use of piped hydrogen make the proposition less daunting. Piped hydrogen doesn’t have the same capacity restrictions that a trucked hydrogen delivery infrastructure will have, however it has very large capital costs and takes a long time to build so is an option when large quantities of hydrogen are being delivered. However it must be planned and started much earlier than it is required.
Analysis on the costs hydrogen transportation by truck and pipe have been performed using the DOE H2 analysis groups hydrogen delivery costs calculator (5). This allows estimations on the cost of hydrogen delivery to be made by choosing an initial scenario. The costs are detailed in the Cost and Economics section.

### 2.2.2 Implications

Hydrogen transportation is necessary for off-site hydrogen generation. The most economical production methods are suited to large centralised production with a distribution network, each certain regions and demand profiles. Early demand will be met using on-site production, with delivery by tube trailer following this and finally a hydrogen pipeline.

### 2.3 Hydrogen Production

In this report the following hydrogen production technologies have been considered:

- Steam methane reforming (SMR)
  - both distributed and centrally;
- electrolysis of water both distributed and centrally,
  - also utilising surplus renewable electricity;
- central biomass gasification
- central production from coal.

Initially hydrogen will be produced by on-site electrolysis and on-site SMR. As demand grows the centralised production technologies will be used. As the longest established technology, central SMR will be implemented first, followed by a mixture of biomass gasification and production from coal. Potential production locations are identified and a cost benefit analysis of production mixtures was performed.

### 2.4 Geographical Implications

As discussed in the hydrogen transportation section the SMR plant needs to be close to the point of use. There is also the need for a large quantity of storage at the site. There are several large scale refineries near large metropolitan areas which currently produce hydrogen via SMR or could potentially be retro-fitted to do so. These sites include facilities in Bayway and Paulsboro in New Jersey which are within 30 miles of Manhattan. The Sunoco and the Marcus Hook refineries near Philadelphia could supply a large quantity of hydrogen to Philadelphia.

Where distributed hydrogen production by electrolysis is used the areas electricity price should be considered. Between New York and Boston the electricity price is between 90 and 125 $/MWh whereas below New York the electricity price is between 70 and 90 $/MWh. The electricity price is the major factor affecting the cost of hydrogen produced by electrolysis, therefore placing electrolysis units between New York and Washington is preferable to placing them between New York and Boston.
3. Evaluation of Locations

This section of the report details the locations that have been highlighted in each phase and in each tier of each phase for the development of a hydrogen refuelling infrastructure. This section is split into four separate main segments representing the three active phases of the project with phase 0 included to show the locations of current refuelling locations.

3.1 Phase 0

There is not currently a fully functional hydrogen infrastructure in the Northeast seaboard of the United States. However research, marketing and outreach projects already exist and facilitate some of the goals within the first phase of the project. Cost savings can be made and objectives can be achieved with less additional stations by working with existing projects. This segment creates a snapshot of the current network of unconnected hydrogen projects.

To source information of the existing refuelling locations a thorough search of available literature was undertaken. Several resources already exist depicting the network that is established, including resources such as DoE reports and strategy maps (6). However, these sources are often convoluted and contradictory. It is difficult to get a clear overview of the nature of each project that is already implemented and especially difficult to incorporate this into a clear and comprehensive overview. As such the team used a number of maps to assess the current picture; an example map is shown for New York below with additional mapping and information provided in Appendix 9.1.

Although Washington was privileged to unveil the first public refuelling station in North America (2004); subsequently it still only has one site available. The original site (Shell, 2004) (7) has closed; the remaining site within the city is a site led by GM and funded by the DoE for training in refuelling fuel cell vehicles and currently it is serving 40 GM lead vehicles (8). In addition one refuelling station is noted for construction to the North West of the city in Morgantown. This is to link into a hydrogen refuelling network connecting with Yeager airport in Charlestown (9).

Philadelphia currently has no publically accessible hydrogen refuelling locations according to the current resources of refuelling locations. However, a refuelling station is operated by air products supplying fuel to fork lift trucks of Syco Ltd in the south of the city (10).

Figure 3 shows the current refuelling stations present in the New York City area (11). New York has some world leading hydrogen projects and currently has 5 refuelling locations. This has to be considered especially during phase I of development as many of these projects facilitate the goals of this phase.

There is only one site already in use within the greater Boston city area, although an additional station is highlighted for immediate development. The area surrounding Albany is a key area to the development and research of the hydrogen economy in general, with numerous, automotive manufacturers, refuelling station developers, gas suppliers and fuel cell manufacturers choosing to locate their Hydrogen research centres in the area.

The Northeast seaboard of the United States currently has 14 operational sites; most are considered private locations and are not accessible to the general public. In addition to locations within the four main population centres there several outlying location. When considering sites for development
within phase I of the project it must be noted that these current locations already facilitate some objectives outlined for phase I and by working with the current projects, cost savings can be made.

![Figure 3 - Hydrogen refuelling stations currently in place in the New York (12)](image)

### 3.2 Phase I

During the first phase the aim is to create a corridor which will facilitate a journey from Boston to Washington; maintaining a maximum distance between stations of 50 miles to prevent range anxiety (13). The main method for evaluating site locations was based on geographical considerations and the distances hydrogen vehicles can travel. Additionally a major focus must be established on the promotion and education surrounding hydrogen; developing the demand for future infrastructure. The development of sites at specific locations incorporated into a larger network can aid this effort; achieved by establishing refuelling stations at, or close to research centres, governmental departments and civic transportation (such as taxis and buses). The nature of the objectives and criteria laid out in previous sections, combined with strategies for development (outlined in later segments) leads to three tiers of priority for locations within phase I.

**Tier 1** - Figure 4 shows 18 locations which have been highlighted for a refuelling station within phase I. Locations shown by red circles are the locations that are required to produce a functional corridor between Boston and Washington and are of highest priority (tier 1). In addition because of the importance of the city of Albany to the hydrogen and fuel cell research community a site has been incorporated to facilitate travel to and from Albany into this corridor.

Tier’s 2 and 3 (shown in green Figure 4) are established into the network and a useable and functional refuelling infrastructure is created that can accommodate active consumers. The sequential development of tiers 1, 2 and 3 is discussed in the development timeline section.

#### 3.2.1 Data Processing

The consideration for locations in phase I is predominantly geographical, with specific locations dependant on individual research projects or local potential. After an approximate location was determined a closer inspection of local potential was undertaken to highlight possible key locations.
3.2.2 Specific location analysis within Population Centres

Following an analysis of the geographic considerations and evaluating the approximate locations needed to produce a functional network. Closer analysis of population centres was conducted. An example of this analysis for Boston is shown with additional information provided in Appendix 9.2.

3.2.3 Analysis for the population centre of Boston

Boston currently has one established hydrogen refuelling station within its greater metropolitan area and one location noted for immediate construction closer to the city centre. However as the area is a key location for the hydrogen fuel research more sites are needed to encourage and link this research. The sites that are currently within the city are not publically accessible. The site highlighted for construction (Logan Airport) under stage 0 is a demonstration project linked to the location already existing to the north of city in a bus project. Led by Nevara Fuel Cell Ltd and the National Fuel Cell Bus Programme this project already facilitates outreach and research requirements in phase I (14). The location at Logan Airport is included in the site selection list below as it would be highly beneficial to make this location publically accessible and reduce the overall cost of the project. It is recommended that this location is made publically accessible or an additional site is added within the city to act as a public refuelling station and increase the range of the Bus Project already in operation. The locations are given below and labelled on the map in Figure 5.

1. Jefferies point at Logan Airport - was chosen due to its central taxi service into Boston and its potential for fleet vehicle use.
2. Boston University - the university site was selected due to its current research into producing hydrogen from municipal waste. (15)
3. MIT - Massachusetts Institute of Technology - chosen for its research into fuel cells and developing hydrogen production combined with solar energy development (16)
4. South Station Bus Terminal - chosen due to its public location and possibility of outreach project similar to European bus projects.
3.3 Phase II

In the 5 year period from 2015 – 2020 it is predicted that the number of vehicles will increase from 100’s to 10,000’s the refuelling infrastructure will have to expand to accommodate this. As with the situation presented in phase I, the criteria for station selection during stage 2 of the infrastructure is further split into three tiers. The criteria for selecting and evaluating these stations changes with each tier moving from individual site locations (tiers 1 and 2) to density functions associated with geographical areas (tier 3). The data evaluation has been performed differently for each tier.

3.3.1 Tier 1 Locations

During tier 1 the upgrades needed to existing stations are included as well as 10 new locations that need to be developed to increase the market size by introducing new geographical areas capable of using hydrogen fuel. The criteria for selecting these locations is primarily the expansion of the network to access a larger market size, these locations are shown in Figure 6, the 10 locations identified as tier 1 during phase II (red), shown against existing stations from phase I (blue). The upgrading of existing stations is essential to being able to supply the demand that is expected.
3.3.2 Tier 2 Locations

At this stage of the project it is anticipated that current refuelling companies will see the demand for hydrogen and become active in supplying hydrogen as a standard fuel. As such the locations identified during tier 2 of phase II include current gas station locations which are in favourable locations meeting the selection criteria. It is recommended that in total 47 locations (discussed in the development timeline section) are prioritised.

3.3.2.1 Data Processing

During tier 2 the network needs to be switched from prioritising geographical, to meeting the demands of the market. As such research was undertaken to discover population densities, income distribution and demographic spreads across the Northeast seaboard.

Income distribution (17), population density (18) and demographic group (19) maps were sourced, re-coloured and layered on a base map to identify areas of specifically high demand Figure 7. Figure 7 shows anticipated high demand (darker) to relative low demand (lighter).

![Figure 7 - Map showing overlays of income distribution, population density and demographic group, darker areas showing higher demand.](image)

3.3.2.2 Station Locations

Each population centre was analysed as shown above with additional analysis for the location of refuelling along inter-city routes. Through analysis of the development timeline in addition to cost and economic assessment, an additional 47 stations were required under tier 2 of phase II. Using the analysis tools developed as described above and repeating for each area of specific interest it was determined that, Boston would require 10 additional stations, New York 10 additional stations, Philadelphia 5 stations, Washington would need 7 and an additional 15 stations were required distributed across the inter-city routes of the Northeast seaboard. The example area of Washington is presented below with additional information provided in Appendix 9.3.

3.3.2.2.1 Washington

By analysing the data collated to show the distribution of expected demand, it was seen that the majority of demand centred to the west of the city. To facilitate this and the traffic density
information gathered, locations are positioned to service demand in the west of the city and major arterial routes as shown in Figure 8.

Figure 8 - New Locations for Washington D.C. under Tier 2 of Phase II

3.3.3 Tier 3 Locations

Tier 3 of phase II is closely linked to tier 1 of phase III, the locations identified in the following sections relate to 160% of the stations required for servicing demand at completion of phase II. The reason for this is the use of private business locations (private fuel suppliers). During tier 3, 81 locations are required, however due to the move to private business which of the 129 identified locations are built under tier 3 is dependent on independent business.

3.3.3.1 Data Processing

The strategy under tier 3 of phase II sees a shift in the methodology for picking stations. Individual locales become ever more influential with geographic requirements being reduced. It was found that retro-fitting gas stations would be economically beneficial. As such locations identified within this tier are based around the positions of existing gas stations. A tabulation method was used to establish the priority number of identified locations. A protocol was established to aid this tabulation.

1) Potential location identified geographically (using Google maps)
2) Location is checked to see if it is real and large enough to retrofit for hydrogen
3) Location is assessed and given ranking on the capacity of station size
4) Surrounding area assessed for percentage of high earners (projects.nytimes.com/census/2010/)
5) Surrounding house value assessed (indicative of land value and affluence)
6) Local population density assessed (arcgis.com/home/webmap/viewer)
7) Information is tabulated and priority ranking given to station
8) The station location (if viable) is added to database of possible locations

3.3.3.2 Station locations

A full database of locations is available on request for example data see Appendix 9.5. Figure 9 shows the locations identified for Phase II tier 3 and Phase III tier 1 within Philadelphia.
3.3.4 Phase II Overview

At the end of phase II 156 locations will have been established (Figure 10).

Figure 10 - 156 locations that are identified in Tier 3 of Phase II and Tier 1 of Phase III.

Phase III

At the beginning of phase III, as many as 300,000 hydrogen vehicles can be expected on the roads in the Northeast region of the U.S. With the core routes covered with filling stations the focus of phase III shifts away from necessity and towards convenience. During phase III refuelling stations will be located in wealthier areas near the homes of the potential customers, often in suburbs outside of the main population centre. All the while filling stations will become increasingly prominent on the highways of the region, with many rest areas and towns housing at least one station. Overall an addition 490 stations will be places in this phase tripling the number of stations in 5 years. As with the previous two phases, Phase III has been split into three tiers, as the focus on necessity has moved to convenience these tiers are objective rather than location orientated.
3.3.5 Tier 1 Locations

Phase II tier 3 and phase III tier 1 are closely linked, with the un-converted remainder of the stations identified during the phase II tier 3 being retrofitted in this stage. At this point there will be a fairly comprehensive network of stations connecting Washington to Boston, with additional stations in place to ensure travel to Albany, and Harrisburg to the west and Richmond to the south. People living in the 4 major cities will have convenient filling locations, whilst those in the identified corridor will be able to fill their vehicles with minimal hassle. In total tier 1 will see 54 stations added to the network.

3.3.6 Tier 2 Locations

The purpose of tier 2 is to increase convenience to our key market. Station distribution is now shown as density rather than on a site by site basis.

3.3.6.1 Data Acquisition

The criteria used are income, population density and current gasoline usage. These together map the target demographic and those who use most fuel. Figure 11 shows a composite image based on these criteria, with the greener regions being areas of higher demand.

![Figure 11 - Map showing overlays of income distribution, population density and gasoline usage](image)

3.3.6.2 Station Locations

During this stage roughly 250 stations will begin to be placed in the green areas not previously covered by prior stations. These stations will be focused at a few key locations; suburbs north and west of Washington, Long Island, towns surrounding Newark, the area surrounding Stamford, and the towns surrounding Edison.

The balance of wealth, population density and current gasoline usage in these areas shows that these people are the most likely to benefit from a transition to hydrogen vehicles as they are most likely to commute distances beyond the range of battery vehicles, as well as having the wealth to afford a switch to what will still be a premium product. Having local stations will increase convenience to this key market and will stimulate growth in car sales. One example of targeted distribution is shown below.

3.3.6.3 Beyond Washington
Examination of the potential demand around Washington shows that the suburbs and towns to the north and west are in greatest need of filling stations. In Figure 12 the darker brown areas have higher potential demand; filling stations will be preferentially placed here. Lighter and blue areas have low demand.

**Figure 12 - Target areas for development around Washington**

### 3.3.7 Tier 3 Locations

By the end of tier 3 there will be 646 filling stations in place across the region making travel around the Northeast states a practical reality. Tier three focuses, with the addition of 190 stations, on expanding outside the corridor and connecting to other cities and regions of the U.S. and Canada.

#### 3.3.7.1 Station Locations

Expansion will be in three directions, firstly, extension north into New Hampshire, Vermont and Maine, whilst these areas have relatively low domestic demand, holiday demand could be high. Extension west towards Rochester, Buffalo and Pittsburgh will allow connection to Canada’s increasingly prevalent hydrogen network and to the mid-west respectively. Extension south will allow connection to the southern states, the extension into these areas will be through introduction of stations into outlying population centres and supporting them through a targeted skeleton network along the key highways highlighted in Figure 13.

**Figure 13 - Targeted Highways for Tier 3 Expansion**
3.4 Hydrogen Production Location Analysis

Hydrogen production is already an established industry across the Northeast seaboard of the U.S. This is used for existing industrial demand so will be neglected at this point, but existing facilities which don’t currently produce hydrogen have been scoped for possible retrofit to enable centralised production plants. Indeed some locations currently use onsite generation to produce the hydrogen used during refuelling.

These locations can help identify voids that cannot be supplied economically with hydrogen during future phases and identify the types of production facility available within a given area. Figure 14 (a) shows the locations capable of producing hydrogen for use in the Northeast U.S.

Figure 14 – (a) Potential hydrogen production facilities, Red - SMR, Green - Biomass generation, Yellow - Nuclear power plants, Blue - Coal power plants, Orange - Wind farms with potential for hydrogen production (b) 100 mile radius showing the economically viable range of supply

Figure 14 (b) shows a 100 mile radius around potential hydrogen production facilities, indicating an economical delivery distance by truck. It shows that in theory, if the production method is not a prerequisite the potential exists to supply hydrogen by trucked compressed gas economically across the Northeast seaboard. However, this is not a true perspective as certain production methodologies are economically and environmentally beneficial and as can be seen in later sections.
5. Development Timeline

This section of the report addresses the development of the hydrogen infrastructure. The objectives, goals and criteria for selection processes have been detailed in previous sections, these are combined and the methodology for achieving these goals is brought together within this section.

In each phase it is important to highlight the combination of hydrogen refuelling locations and the sourcing, production and supply of hydrogen to these locations. As the network is developed the types of refuelling station, method of hydrogen delivery and method of hydrogen production used changes due to the economics at each stage of increased demand from the market.

As with other sections the development timeline is broken into phases and tiers representing key milestones where objectives have been outlined, demand has reached certain levels and supply techniques need to expand. These match the phases and tiers of previous sections. A brief summation of each is given below,

Phase 0 – describes the current landscape associated with hydrogen refuelling, production and supply within the Northeast seaboard of the U.S.

Phase I – split into three further tiers, phase I encompasses the development of an early adopter market.

- Tier 1 – represents the very first stages of the early market, principle concern is the quick establishment to supply hyper-early market pioneers.
- Tier 2 – denotes the second stage of the early market, introducing early-adopter consumers.
- Tier 3 – the final stage of establishing an early market, with the focus on securing an infrastructure capable of expansion into a functional market place whilst supplying an early adopter fleet.

Phase II – principally focusing on using the established early market and penetrating into the main transport market, this phase is split further into three tiers.

- Tier 1 – concentrates on cementing the position of the early market and allowing future access to a larger market through geographic expansion of the network.
- Tier 2 – develops the capacity of the established network to service the demand of an increasing developing market.
- Tier 3 – completes the move from developing the market in logistical terms to a fully incorporated economically driven market with individual private business increasing influence on the developing supply chain.

Phase III – Directs the development towards complete commercialisation, achieved through three tiers.

- Tier 1 – Increases the incorporation of private business into the supply chain whilst supplying a drastically increased market size.
- Tier 2 – Consumer specific development of the infrastructure expanding capacity and driving increased demand.
Tier 3 – Complete commercialisation of the network and developed links to separate areas of hydrogen infrastructure outside the region of concern.

5.1 Phase I

Phase I represents the time period 2013-2015 and is the first active phase of this project. As has been mentioned earlier in criteria development and evaluation of locales sections, the phase is split into three tiers of priority. This allows for prioritisation during development and for managing the transition across the phase.

5.1.1 Refuelling locations

The deconstruction of phase I into three tiers allows for the management of this essential stage in developing the network of refuelling locations.

5.1.1.1 Tier 1 - establishing 7 refuelling locations to supply hyper-early adopters, principally research associated consumers.

An important obstacle to overcome is the barrier to entry for both consumers and suppliers to the market that is the incoherent supply of hydrogen refuelling. Consumers cannot create demand for refuelling without being capable of purchasing vehicles that can travel to desirable destinations. To overcome this issue an instantaneous role out of a skeleton infrastructure is desirable and only achievable with the use of portable refuellers. To facilitate journeys across the region of concern it was established 7 sites are required as a bare minimum.

Figure 15 - Tier 1 Phase I, 7 locations identified with 75 mile radius showing maximum travel distance of fuel cell vehicles
5.1.1.2 Tier 2 – Establishing a total of 14 refuelling locations, to provide refuelling to an expanding early-adapter market.

The seven locations of tier 1 cannot support any more than a small vehicle base. As such whilst these 7 stations are in position, a permanent refuelling station is built at the same location. As the permanent sites are built the portable refuellers are relocated to other positions enabling the quick expansion of the network under tier 2 of phase I. This methodology allows for rapid expansion of the market, instilling consumer and supplier confidence and reducing barriers to entry for consumers and suppliers alike.

5.1.1.3 Tier 3 – Completion of an early market infrastructure with a total of 18 refuelling locations.

To complete a functional initial refuelling network an additional four stations need to be added; servicing early adopter consumers and providing the ability to travel across the Northeast seaboard with relatively little hindrance.

![Figure 16 - Tiers 2 & 3 of phase I, new locations shown in red, existing in blue, green circle represents 25km radius from each station]

Phase I is designed to produce a functional network of refuelling points as quickly as possible and for the cheapest economic cost. During phase I some of the permanent stations need to be upgraded in order to be able to supply sufficient hydrogen each day to meet anticipated demand. The reason for choosing a programme where portable stations are replaced by small, and then some small stations are upgraded to mediums during phase I, is the comparison in capital cost and construction time of these stations. Retrofitting existing gas stations reduces costs as well as potentially welcoming private fuel supply companies on-board the programme, also reducing the time to establish a functional network. This functionality of the network is seen as a key goal to inspire consumer confidence and help establish sustained demand in hydrogen fuelled vehicles.
In the short term the capital investiture of establishing a skeleton network of small stations is again simpler, cheaper and quicker to achieve, than to build larger stations. As such, during the first phase of the programme small stations are to be used in order to quickly establish a consumer friendly network in a relatively small space of time. A number of these stations, typically within the major population hubs need to be increased to a medium size station during this phase. This is not an ideal situation retrofitting a station so soon after initial construction. However, it is seen as the best way to maximise a quick role out within the early stages of network development, securing a functional and consumer ready infrastructure, allowing people to drive in relative ease, which is essential to establishing a market.

5.1.2 Hydrogen Supply

The method of supplying hydrogen during phase I is kept relatively simple due to the nature of the network required. Due to the need to facilitate a network quickly and knowledgeable that the price of hydrogen is weak to fluctuations in market demand; it is recommended that although existing infrastructure exists which could support the supply of hydrogen, on-site production is to be used. As a result the needs for supply are reduced.

This is not to say a supply network does not need to be initialised. Increases in peak hydrogen refuelling may create the need to deliver hydrogen on-site to facilitate peak demand periods. However as has been show in previous sections almost all stations lie within economical distribution distances for compressed gas hydrogen delivery from existing production facilities. Supplies of water, electricity and natural gas will need to be established. Water demand of onsite water electrolysis is relatively low with each car using less water per day than a single flush of a toilet. With on-site SMR natural gas supply to the site is provided by tapping into the existing natural gas supply network existing across the area.

5.1.3 Hydrogen Production

During the first phase the project, it is recommended that on-site production of hydrogen is used. This is to achieve an efficient and robust skeleton infrastructure during tier 1. To facilitate this, onsite water electrolysis is recommended to be combined with the portable refuellers, to quickly establish a functional network in tier 1. In the second tier the small sites built are designated to use onsite-SMR, this is to both spread the risk of depending on one raw product in the production of hydrogen and the capital cost of this method of production, in which the on-site water electrolyser travel in conjunction with then portable refuellers to new sites. In tier 3 it is an aim to convert...
several more small permanent sites, with the upgraded medium stations all utilising on-site SMR hydrogen production.

Figure 18 - Percentage split of hydrogen sourcing, number and percentage distribution of the type of station utilised across Phase I

5.2 Phase II

Phase II is the period of development that evolves the skeleton infrastructure, that supplies an early adopter market, transition into an infrastructure capable of supporting an emergent market. This results in the penetration of the main transport sector and realising the potential of hydrogen as a transportation fuel. As with phase I the transition is managed through three tiers of distribution which break the dramatic increase in infrastructure into manageable segments each with a shift in objective and focus.

5.2.1 Refuelling locations

During phase II, the capacity and the distribution of the refuelling network needs to increase dramatically to match the anticipated increase in demand. It is essential that the network spreads geographically to exploit potential centres of demand and allow access for those consumers to the market whilst managing the increase in supply required to provide for the increase in consumers in existing centres of demand.

Figure 19 - Predicted number of active Fuel cell Vehicles during Phase II, predicted maximum and minimum required capacities versus planned, installed capacity

Tier 1 of development sees the network increase from 18-28 station whilst increasing the capacity of existing stations to meet demand. The 10 new locations introduced expand the geographical size of the market allowing access to consumers in areas across the Northeast seaboard. This is to ensure
that early-adopters in these areas are introduced to the market whilst allowing penetration into the regular transport sector by moving out of the early-adopter market in the key centres of demand along the corridor of travel. This is achieved through the increase in capacity of existing stations within these areas.

Tier 2 sees an effort concentrated on establishing the extra capacity required within the network whilst creating a refuelling infrastructure more familiar to regular consumers in the transportation sector. It sees the number of stations increase from 28-75 with the additional stations positioned to focus on exploiting key areas of demand on a more focused level. These stations are positioned to service specific demand centres within key locations and across key routes of travel.

Tier 3 of this phase manages a transition in policy for the direction of network with an increase from 75-156 stations. This sees the migration to facilitating the expansion of private business in the refuelling sector. As such the project identifies key areas of demand and aims to facilitate this demand by retrofitting existing gas stations. The positioning of locations for refuellers relies heavily on the precise economics of the locations, with local cost factors a major contributing factor in development. This situation occurs as the market has successfully evolved into a pre-developed market with significant consumer demand.

5.2.2 Hydrogen Supply

During phase II it is anticipated that the majority of the hydrogen will be transported by truck with some of the major routes being supplied by pipeline. The pipeline has been designed to cover the region with the highest demand and highest electricity price first coupled to existing natural gas routes, such as the Algonquin pipeline (20). By placing the pipeline where the electricity price is high the cost of hydrogen can be reduced by placing on site electrolysers in areas where electricity is cheap.

5.2.3 Hydrogen Production

During this phase the variety of sources for hydrogen increases. Whereas the first phase was predominantly distributed electrolysis or SMR, during phase II centrally produced hydrogen becomes important, due the rate at which demand grows. SMR is the most important technology during this phase, and accounts for 40% of hydrogen production by 2019. There is also smaller contributions from coal and biomass production.

Phase II manages the transition from an early market to the initial penetrations into the main transportation market of the Northeast seaboard of the U.S. After the initial introduction of the skeleton network of phase I (tier 1), the successful management of this transition, specifically during tier 2 of phase II is essential in determining the overall success of producing an economically successful hydrogen economy across the seaboard.
5.3 Phase III

Phase III sees a rapid development of infrastructure, changing the hydrogen landscape from a narrow corridor to a convenient commercially viable network spanning the Northeast region. Managed through three tiers of integration, tier 3 sees the Northeast connect to other regions to form part of a wider U.S. hydrogen infrastructure.

5.3.1 Refuelling locations

Tier 1 extends the work of tier 3 in phase II. This will cement a solid, complex network connecting the Northeast U.S.

Tier 2 focuses largely on the urban centres outside of the 4 main cities. Having a hydrogen highway in place will make these the target areas for market expansion and hence warrant greatest attention, through the introduction of 250 stations.

Tier 3 connects the network across the seaboard, expansion inland will allow for connection to the mid-west and Canada. At this point, with other regions rolling out hydrogen as a fuel it will be possible to justify the use of a fuel cell vehicle for trans-continental travel.
5.3.2 Hydrogen Supply

During phase III, hydrogen switches to a mix of production techniques, with a high level of centralised production and distribution. Phase III sees the development of hydrogen pipelines from centralised production centres to regional hubs, from where trucks will deliver fuel to individual stations. Towards the end of the phase, introduction of stations receiving hydrogen direct from pipeline will begin to emerge.

5.3.3 Hydrogen Production

The hydrogen production becomes dominated by central SMR during this period. Central electrolysis is the other major hydrogen production method during this phase as the quantity of renewable electricity grows. However central electrolysis is still one of the most expensive ways of producing hydrogen and to the greatest extent possible this is done using surplus renewable electricity. Biomass also plays an important role in the early stages of phase III as it is cheap, green and renewable. Therefore the maximum quantity possible is used, however the percentage of total hydrogen supply falls rapidly as the production is maximised. From NREL data indicating that 12,000 kg H2/sq.km/year (21) can be produced by biomass, and assuming a production area of 160,000 km with 1% utilisation the maximum hydrogen which can be supplied is 20 million kg/year, which is around 12% of the total supply requirement.

![Figure 22 - Percentage split of hydrogen sourcing, number and percentage distribution of the type of station utilised across Phase III](image)

5.4 Phase IV

Phase IV will witness transition to free market economics. Over time as hydrogen vehicles gain an ever larger market share the hydrogen distribution network will come to mirror the current gas distribution network, with numerous stations available in a given location. In the distant future home electrolysis units will allow customers to fuel themselves, which will dramatically alter the distribution landscape. In what will be a considerable enhancement over the existing distribution of gasoline, the ideal scenario will be that a significant quantity of hydrogen is delivered through pipelines from centralised facilities. Those stations outside the piped network will increasingly rely on distributed SMR and electrolysis, with the latter benefitting from increased uptake of renewable energies, utilising excess wind power overnight. A significant minority will continue to have hydrogen delivered by truck for economic reasons. Hydrogen production will be, in an ideal future almost wholly reliant on hydrogen produces from renewable sources, created centrally, this will piped to individual stations mirroring natural gas distribution. Over time private citizens may have access to this pipeline, or even at-home electrolysers, using photovoltaic panels to power electrolysers through the day.
6. Cost and Economic Analysis

This section investigates the costs associated with each phase and cumulative cost of the proposed hydrogen sourcing and refuelling infrastructure. In this section the report considers; the cost of hydrogen production, including variable and capital costs; the cost of hydrogen delivery; the cost of hydrogen refuelling stations. Finally the hydrogen selling price will be discussed with a view to making profit within the next 20 years.

6.1 Principle Costing’s

6.1.1 Refuelling

The types of the stations, their capacity and their fixed capital cost, including infrastructure, compression and dispensing are shown in the table below.

<table>
<thead>
<tr>
<th>Station</th>
<th>Capacity (kg/day)</th>
<th>Capital Cost ($/thousands)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portable</td>
<td>100</td>
<td>1,000</td>
<td>(22)</td>
</tr>
<tr>
<td>Small</td>
<td>250</td>
<td>2,500</td>
<td>(22)</td>
</tr>
<tr>
<td>Medium</td>
<td>400</td>
<td>2,800</td>
<td>(22)</td>
</tr>
<tr>
<td>Large</td>
<td>1,000</td>
<td>5,050</td>
<td>(22)</td>
</tr>
</tbody>
</table>

The station running costs are calculated from analysis made by Ball et al. (23), they include a baseline cost and cost / kg, electricity cost / kg, property tax, property rent, insurance and permit fees. These are approximately 10% of the station capital costs agreeing with estimates by Coulson and Richards (24).

From the data provided on the total hydrogen requirement on a year-by-year basis, we were able to calculate the quantity of refuelling stations required from the station capacities as shown in Table 1 above. This analysis shows that approximately 650 refuelling stations are required in the Northeast U.S. in order to meet consumer demand by 2025.

6.1.2 Production

The technologies recommended for producing hydrogen for the refuelling stations are SMR, electrolysis, coal and biomass gasification. Examples of hydrogen production facilities, including capacity and costs were taken from literature and used as a basis for the implementation of the production infrastructure. Fixed capital, maintenance (ancillary) and variable costs are shown for each technology in the table below. Costs include price of purification and compression (in line with regulations and standards).

The annual hydrogen requirement and the available technologies to produce hydrogen were used to produce a suitable roll out plan of hydrogen sourcing infrastructure. Using the predetermined sizes of hydrogen production facilities, estimated minimum and maximum potential hydrogen requirements (Figure 1) were used to ensure the hydrogen production infrastructure met the hydrogen demand.
<table>
<thead>
<tr>
<th>Technology</th>
<th>Capacity (kg/day)</th>
<th>Capital Cost ($000s)</th>
<th>Ancillary Cost per year ($000s)</th>
<th>Variable Cost ($/kgH₂)</th>
<th>Costs Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central SMR</td>
<td>120000</td>
<td>35310</td>
<td>3531</td>
<td>1.12</td>
<td>(23)</td>
</tr>
<tr>
<td></td>
<td>5760</td>
<td>3923</td>
<td>392</td>
<td>1.12</td>
<td>(23)</td>
</tr>
<tr>
<td>Distributed SMR</td>
<td>371</td>
<td>253</td>
<td>25</td>
<td>2.00</td>
<td>(25)</td>
</tr>
<tr>
<td>Central Electrolysis</td>
<td>5760</td>
<td>3139</td>
<td>314</td>
<td>4.24</td>
<td>(23)</td>
</tr>
<tr>
<td>Distributed Electrolysis</td>
<td>427</td>
<td>233</td>
<td>23</td>
<td>4.95 (grid)</td>
<td>(26)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.10 (renewable)</td>
<td></td>
</tr>
<tr>
<td>Centralised Coal Gasification</td>
<td>3000</td>
<td>36000</td>
<td>3600</td>
<td>0.96</td>
<td>(27)</td>
</tr>
<tr>
<td>Centralised Biomass Gasification</td>
<td>12000</td>
<td>458</td>
<td>46</td>
<td>0.50</td>
<td>(23)</td>
</tr>
</tbody>
</table>

### 6.1.3 Hydrogen Delivery

Calculating a cost for hydrogen delivery proves difficult, with the costs being heavily reliant on distribution distance, volume delivered and population density. Truck transport benefits from low capital costs, however with low volume capabilities, would be unsuitable to support a wider distribution network. Pipelines require large capital investment, with low transmission costs. A hybrid network of the two provides a medium term cost balance with short distances travelled by truck from regional distribution hubs supplied by pipeline. In this report we have used a tool to calculate the cost of hydrogen delivery (5). The tool has been produced by the DOE and allows the user to specify a number of parameters including:

- Population density
- Market penetration
- Distribution method
- Station size
- Refuelling pressure

Figure 23 shows the cost of hydrogen production using the tool and values which represent the scenario at each stage as closely as possible. Up until 2017, prohibitively high costs require sites to produce their own hydrogen through onsite SMR or electrolysis. As of 2017, truck delivery from central production centres becomes prevalent, until further development sees the establishment of local distribution hubs. These hubs will be supplied by hydrogen pipelines with distribution being by truck, these hubs will begin to be viable in 2021.
6.1.4 Summary

Yearly cost of hydrogen delivery, refuelling stations (capital and running), hydrogen production cost, and hydrogen production plant costs (running and capital). The relatively low cost of hydrogen plants is due to the few centralised production facilities which produce sufficiently high quantities of hydrogen to supply many stations.

The hydrogen cost includes a hydrogen tax of $0.50/kg \( H_2 \), assuming the average U.S fuel tax of 0.49$/gallon and 1 kg \( H_2 = 1 \) Gasoline Gallon Equivalent (GGE) (28). Currently hydrogen doesn’t have any fuel tax in the majority of the states covered by this report (29); however as the penetration of hydrogen fuel grows it is likely that a fuel duty will be applied.

The total accumulative variable and fixed costs has been calculated to be $5.5 billion by 2025.
6.2 Financial Incentives

Directed by federal government cost competitiveness can be increased by making use of the various regulatory incentives that are available. The majority of incentives take the form of tax credits or low-interest loans directed at improving the energy security or air quality within the U.S. These are applied for by the separate actors within the market. These are not directly factored into the costing of the infrastructure designed, partly because of the necessity for the market to survive independently of federal direction after the completion of phase II but also because these incentives can be seen as a predominant driver for private business to enter the market.

6.3 Hydrogen Price

To set a price ($/kg) for the hydrogen to be sold, it must be economically competitive with conventional gasoline vehicles in the long term. It must also represent an investment opportunity for the bodies that implement this refuelling structure i.e. be profitable in the long term. Balancing these two factors is crucial to the successful integration of hydrogen fuel cell vehicles in the transportation sector for the Northeast U.S.

The graph below shows the balance sheet for various prices of hydrogen and the expectant return on investment for the period up to 2025 and the way this is predicted to develop up to 2045.
Figure 25 - Predicted Profit and Loss for a range of hydrogen selling prices from $6.50 to $9.50 /kg.

6.4 Return on Investment Analysis

A reasonable break even duration for a project of this scale is 25-30 years after the initiation of the project. The project start point was 2013, which means a breakeven point between 2038 and 2042 would be a reasonable period to attract investors to the project. Setting a price of $6.75/kg H\textsubscript{2} gives annual profitability in 2031 and a breakeven point in 2040. A selling price of $6.75 is comparable to a gasoline price of ~$3.40/Gallon, assuming that a fuel cell vehicle is twice as efficient as a gasoline vehicle and 1 kg hydrogen is equivalent to 1 GGE. Increasing the hydrogen selling price to $7.50 /kg H\textsubscript{2} would reduce the payback time to 2032, but consumer uptake maybe affected.

Figure 26 - Cumulative Profit and Loss with a hydrogen price of $6.75/kg H\textsubscript{2}.
7. Regulations Codes and Standards

This section of report describes the codes, standards and regulations that relate to establishing a refuelling network across the Northeast seaboard of the United States. It also details how the project team has considered applicable rules, regulations and codes in the methodology used to establish a refuelling network.

Hydrogen has been a commercial product for over a hundred years and has received intense interest in recent years (30). This has led to a comprehensive list of codes, regulations and standard being established, in recent years the appropriate regulations have undergone scrutiny to reduce contradictions in reference to Hydrogen refuelling. The nature of this project means that multiple jurisdictions overlap and each has their own specific rules, codes and regulations which must be considered.

Establishing a general baseline is essential to allow the project to develop, considering important legal issues, specific incentives which could relate to the project and to produce a safe reliable consumer friendly network. The following table summarises the rules regulations and codes that were used to evaluate locations and to model the development of the overall network.

Each of the states intended for inclusion into the hydrogen highway have their own respective bodies for buildings & construction, energy & environment, emergency services, transportation, motor vehicles and education. Massachusetts, Connecticut, Rhode Island, New York State, Pennsylvania, New Jersey, Maryland, Virginia and Delaware are the relevant states. The U.S. Department for Energy (DOE) has established a collection of all relevant legislation and state incentives (Energy 2012)

7.1 Codes, regulations and standards related to hydrogen

<table>
<thead>
<tr>
<th>Association</th>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFPA (National Fire Protection Agency)</td>
<td>2</td>
<td>The purpose of this code shall be to provide fundamental safeguards for the generation, installation, storage, piping, use, and handling of hydrogen in compressed gas (GH2) form or cryogenic liquid (LH2) form. 1.3* Application. 1.3.1 This code shall apply to the production, storage, transfer, and use of hydrogen in all occupancies.</td>
</tr>
<tr>
<td>70</td>
<td></td>
<td>Adopted in all 50 states, the National Electrical Code is the benchmark for safe electrical design, installation, and inspection to protect people and property from electrical</td>
</tr>
<tr>
<td>Standard</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>NEC (National Electrical Code)</td>
<td>Addresses installation of electrical conductors, equipment, and raceways; signalling and communications conductors, equipment, and raceways; and optical fibre cables and raceways in commercial, residential, and industrial occupancies.</td>
<td></td>
</tr>
<tr>
<td>ISO (International Organisation for Standardisation) ISO 15916:2004</td>
<td>Provides guidelines for the use of hydrogen in its gaseous and liquid forms. It identifies the basic safety concerns and risks, and describes the properties of hydrogen that are relevant to safety. Detailed safety requirements associated with specific hydrogen applications are treated in separate International Standards.</td>
<td></td>
</tr>
<tr>
<td>ISO 14687-2:2012</td>
<td>Specifies the quality characteristics of hydrogen fuel in order to ensure uniformity of the hydrogen product as dispensed for utilization in proton exchange membrane (PEM) fuel cell road vehicle systems.</td>
<td></td>
</tr>
<tr>
<td>ISO 22734-1:2008</td>
<td>Defines the construction, safety and performance requirements of packaged or factory matched hydrogen gas generation appliances, herein referred to as hydrogen generators, using electrochemical reactions to electrolyse water to produce hydrogen and oxygen gas.</td>
<td></td>
</tr>
<tr>
<td>SAE (Society of Automotive Engineers) J 2600-2012 ©</td>
<td>Compressed Hydrogen Surface Vehicle Refuelling Connection Devices. Applies to the design and testing of Compressed Hydrogen Surface Vehicle (CHSV) fuelling connectors, nozzles, and receptacles. Connectors, nozzles, and receptacles must meet all SAE J2600 requirements and pass all SAE J2600 testing to be considered as SAE J2600 compliant. This document applies to devices which have Pressure Classes of H11, H25, H35, H50 or H70.</td>
<td></td>
</tr>
<tr>
<td>SAE TIR J2601/2</td>
<td>Fuelling protocols for light duty gaseous hydrogen surface vehicles and ½ for buses</td>
<td></td>
</tr>
<tr>
<td>J 2719-2011 by ANSI (American National Standard Institute)</td>
<td>This Standard provides background information and a hydrogen fuel quality standard for commercial proton exchange membrane (PEM) fuel cell vehicles. This Report also provides background information on how this standard was developed by the Hydrogen Quality Task Force (HQTTF) of the Interface Working Group (IWG) of the SAE Fuel Cell Standards Committee.</td>
<td></td>
</tr>
<tr>
<td>ASTM (American Society for Testing and Materials) ASTM D7606</td>
<td>Standard Practice for Sampling of High Pressure Hydrogen and Related Fuel Cell Feed Gases This practice is intended for application to high pressure, high purity hydrogen; however, the apparatus design and sampling techniques may be applicable to collection of other fuel cell supply gases.</td>
<td></td>
</tr>
<tr>
<td>D7650</td>
<td>Test Method for Test Method for Sampling of Particulate Matter in High Pressure Hydrogen used as a Gaseous Fuel with an In-Stream Filter</td>
<td></td>
</tr>
<tr>
<td>D7651</td>
<td>Test Method for Gravimetric Measurement of Particulate Matter</td>
<td></td>
</tr>
<tr>
<td>Organization</td>
<td>Document/Standard</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>IEC (International Electrotechnical Commission)</td>
<td>IEC 61508</td>
<td>Functional Safety of electrical and/or electronic elements. Functional safety is a concept applicable across all industry sectors. It is fundamental to the enabling of complex technology used for safety-related systems. It provides the assurance that the safety-related systems will offer the necessary risk reduction required to achieve safety for the equipment.</td>
</tr>
<tr>
<td>AIAA (American Institute of Aeronautics and Astronautics)</td>
<td>AIAA Guide to Safety of Hydrogen and Hydrogen Systems (G-095-2004e)</td>
<td>This Guide presents information that designers, builders, and users of hydrogen systems can use to avoid or resolve hydrogen hazards. Guidelines are presented for system design, materials selection, operations, storage, and transportation. Pertinent research is summarized, and the data are presented in a quick-reference form.</td>
</tr>
<tr>
<td>International Fire Code (2009)</td>
<td></td>
<td>It covers equipment location and setbacks, setback reducing barriers, indoor installations, annual inspections, piping and tubing, valving and fittings, gaseous and liquid storage, canopy top equipment and gaseous storage, dispensing operations, protection from vehicles, E-stops, venting, pressure relief devices, signage, fire suppression, detectors, vent pipe separation and distances.</td>
</tr>
<tr>
<td>CGA (Compressed Gas Association)</td>
<td>G-5.4©</td>
<td>Standard for Hydrogen Piping Systems at Consumer Locations</td>
</tr>
<tr>
<td></td>
<td>G-5.5©</td>
<td>Hydrogen Vent Systems</td>
</tr>
<tr>
<td></td>
<td>P-1©</td>
<td>Safe Handling of Compressed Gases in Containers</td>
</tr>
<tr>
<td></td>
<td>P5-20©</td>
<td>Direct Burial of Gaseous Hydrogen Storage Tanks</td>
</tr>
<tr>
<td></td>
<td>P5-21©</td>
<td>Adjacent Storage of Compressed Hydrogen and Other Flammable Gases</td>
</tr>
<tr>
<td></td>
<td>S-1.3©</td>
<td>PRD Standards Part 3 - Stationary Storage Containers for Compressed Gases</td>
</tr>
<tr>
<td>ASME (American Society for Mechanical Engineers)</td>
<td>B31.3©</td>
<td>Process Piping</td>
</tr>
</tbody>
</table>
7.2 Application of codes, regulations and standards related to hydrogen

After formulating a base list of appropriate codes, regulations and standards they were assimilated into related subjects to be applied to the development of infrastructure. The general categories considered were, evaluation, costs, production (supply), public awareness, and operation.

7.2.1 Refuelling station

During the analysis period of this project the rules and regulations adjudged to be within this section were used to evaluate the potential a certain location had for refuelling, production or supply. The main criteria which can be deduced from regulations for the evaluation of these sites is the size of locations. The regulations related to hydrogen refuelling stations indicates a minimum separation of components within the refuelling station. These separation distances are universal regardless of the size of station. These regulations were simplified and a diagram produced for the team to work from. This was completed for a small, medium and large station mock-up with the restriction sizes being identical for each, with just the physical storage capacity and number of refuelling points changing.

![Figure 27 - Spatial restriction on station components](image)

This 3D representation can then be overlaid onto images of the physical environment to see if a location is suitable for the designated size of station, Figure 28.
Codes Regulations and standards also affected the decision surrounding the methodology used to roll-out the network of stations. It was known that portable refuellers, as used in the Californian roll-out strategy, already meet the required rules, codes and regulations and the main consideration when installing are the safe minimum distances for components. This greatly aids the quick roll-out during tier 1 of phase I and subsequently the development into tier 2.

An example of where general rules and regulations can be overcome with specific legislations is the, Getty station, 747 Main Street, New Rochelle, NY, 10805, part of phase II tier 1. This station measures approximately 28 m by 23m. The northeast and southeast sides have pedestrian and motor vehicle access, whilst the northwest and southwest side back onto private property/residential areas. Due to the small and restricted nature of the sight the utilisation of passive means to reduce necessary safety distances should be implemented. A hydrogen enclosure would implement a fire retardant structure capable of a burn time of over 2 hours, allowing the distances to other flammable gas storage, combustible materials, utilities, parked cars and exposed person, building openings and lot lines all to be reduced by half. This is covered by the NFPA document 55 code 10.3.2.4. Thus the unit will be placed 5 metres away from the lot lines, no building openings are visible within the 5 metre radius. Compressors and HVAC must still be kept the full 10m away, exposed personnel must be kept a minimum 2.5m away and no flammable gas storage or combustibles should be placed anywhere within the 2 m radius.

7.3 Purity

The purity of hydrogen is very important for fuel cell vehicles and the purity of hydrogen delivered from a pump will have to meet minimum standards. These are currently covered by the regulation SAE J-2719 – 2011 which defines the purity of hydrogen at the nozzle to have 100 ppm of less of total non-hydrogen, with oxygen at 5ppm or less, water at 5 ppm or less and CO at 100 ppb or less.
7.4 Pipeline

Hydrogen has been transported by pipelines for many years, although over very short distances compared with a federal hydrogen infrastructure. As such codes, standards and regulations are relatively outdated (31). ASME has set up the B31 committee tasked to update this regulation alongside the Department of Transport (DOT) and DOE (32). Currently work is focusing on upgrading existing natural gas pipelines and whether existing infrastructure is capable of running hydrogen. Much discussion centres on hydrogen embrittlement (33), although not definitive yet, results published suggest that natural gas pipelines could be converted to transport hydrogen with relatively little investment (34). When discussing the development of the piped hydrogen network within this project, focus has been on using existing natural gas infrastructure, to either partner or be replaced by hydrogen lines. Such as the Agonquin gas transmission line. This dramatically reduces the capital costs of establishing a piped infrastructure.

7.5 On site production

NFPA document 55 code 12 allows the positioning of electrolysers on station roof tops which could provide a significant space saving. NFPA 55 - 12.3.2.5.3 states that the roofing material within 12 inches with any hydrogen component will be non-combustible with compliance to the building regulation code. Electrolysers shall be tested and approved in accordance ISO/DIS22734, hydrogen generators using the water electrolysis process. Catalytic converters can also be positioned on rooftops, NFPA 55- 12.3.2.8.2.1 states that the area contained by the catalytic reformer must be located such that any HVAC intakes, doors, windows and other openings can’t be exposed to hazardous atmospheres or toxic gasses. Section 703 (IFGC) states that the rate of hydrogen production can’t exceed 0.1 m$^3$/min (13 kg/day) per 250m$^2$ of floor space without suitable ventilation being installed.

7.6 Incentives for the establishment of a hydrogen infrastructure

In the recent decade there has been much federal direction (both within Bush (35) and Obama (36) administrations) towards fuel policy and switching from purely imported petroleum fuels. As such there are a raft of regulatory incentives that are available to support the development of a hydrogen infrastructure. In the most part these take the form of tax credits (such as the hydrogen infrastructure tax credit (37)) or low-interest loans (such as the improved energy technology loan scheme (38)) for actors within the market who can prove an increase in energy security as a direct result of their efforts. Contributing efforts to increasing energy security is defined by the DoE and DoT and apply both federally and by jurisdiction.

There are a number of regulations, codes and standards which effect the cost and economics of implementation dramatically. These increasing construction costs due to necessary permits and testing requirements or alternatively, reducing the costs of supply and locations by offering regulatory incentives.
8. Marketing and education Outreach plan

In order to successfully implement hydrogen fuel into the consumer market, it will be important to consider a comprehensive marketing plan. Ideally, this plan will be implemented before and in conjunction with the development of the hydrogen infrastructure in order to increase the awareness, drive demand and to alleviate fears regarding hydrogen and fuel cell technology. As such, outreach education will be integral to the success of the uptake of fuel cell vehicles. This marketing plan will therefore include outreach and education. It will be important to have marketing and advertising of hydrogen and fuel cells at all stages of the development of the hydrogen infrastructure.

8.1 Education Outreach

We have identified the groups that require education in hydrogen technologies and considered appropriate means to communicate the benefits and safety considerations of hydrogen vehicles so as to raise awareness, alleviate fears and build a demand base. The following table outlines the key stakeholders we have identified and our plans for engaging with these groups (39).

<table>
<thead>
<tr>
<th>Task</th>
<th>Key stakeholders</th>
<th>Current DoE activities in the region</th>
<th>Planned activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1.1</td>
<td>Emergency service professionals</td>
<td>An “Introduction to Hydrogen Safety for First Responders” project has designed course modules (40)</td>
<td>Engaging with decision makers to ensure these training programmes are recognised and compulsory.</td>
</tr>
<tr>
<td>1.1.2</td>
<td>Safety officers (e.g. in construction)</td>
<td>The “Introduction to Hydrogen for Code Officials” information package includes details about codes and standards (41)</td>
<td>Promote involvement with providing infrastructure. Encourage communication through existing channels with potential end users, general public and schools</td>
</tr>
<tr>
<td>1.1.3</td>
<td>State and local governments</td>
<td>A database of state demonstrations, policies and initiatives has been put together and is available online, and there are regular informational calls and public webinars (42)</td>
<td>Engage with the press to release success stories. Target outreach for example by advertising in car magazines and presence at trade shows for fleet vehicle operators. All advertising materials would link to a user-friendly website. Local seminars near to fuelling station sites.</td>
</tr>
<tr>
<td>1.1.4</td>
<td>Business end users</td>
<td>Case studies of hydrogen technologies in action, economic tools to assess the business case for hydrogen, and introductory information for potential end users are all available online (43)</td>
<td></td>
</tr>
<tr>
<td>1.1.5</td>
<td>General public</td>
<td>Online informational materials (44)</td>
<td></td>
</tr>
<tr>
<td>1.1.6</td>
<td>University staff and students</td>
<td>Curricula have been prepared for undergraduate and graduate education, and the Hydrogen Design Contest has been set up (45)</td>
<td>Promote directly with university departments not yet researching in the area.</td>
</tr>
<tr>
<td>1.1.7</td>
<td>School teachers and pupils</td>
<td>“H2 Educate!” for middle schools and “Hydrogen Technology and Energy Curriculum (HyTEC)” for high schools have been prepared and can be adapted to state curriculum requirements. These</td>
<td>Promote directly with schools. Provide opportunities for schools to visit successful implementations or to have hydrogen vehicles available, e.g. at science festivals</td>
</tr>
</tbody>
</table>
are promoted through conferences and supported by CPD events (46)

8.2 Marketing Sectors Methodologies

<table>
<thead>
<tr>
<th>Task 1</th>
<th>Key Sectors</th>
<th>Marketing Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2.1</td>
<td>Government</td>
<td>In order to aid with the implementation of governmental policy, it will be important to directly target policy makers and local government. This will achieved through direct advertising through political newspapers/journals as well as advertising in the more affluent metropolitan areas.</td>
</tr>
<tr>
<td>1.2.2</td>
<td>Young Adults (10-20 years)</td>
<td>Young adults will be a very important sector to target as they will be in a position to drive H₂ vehicles by phase III of the implementation plan. As such Media based advertising through viral ad campaigns along with adverts for H₂ vehicles in the cinema will be most important.</td>
</tr>
<tr>
<td>1.2.3</td>
<td>Adults (&gt;21 years)</td>
<td>By phase III, the adult sector will be vital. These adults will the ones with the purchasing power to make H₂ vehicles successful. Targeted marketing campaigns will be most important, particularly focussed on the more affluent adults. This could be achieved by placing billboard adverts in affluent areas and placing adverts in “higher class” newspapers/journals.</td>
</tr>
<tr>
<td>1.2.4</td>
<td>Business end users</td>
<td>Commercial applications will potentially be a large sector for H₂ vehicles, especially companies with fleets. Advertising to this sector will involve advertising at tradeshows, e.g. at fleet manager conventions and in trade magazines.</td>
</tr>
<tr>
<td>1.2.5</td>
<td>General public</td>
<td>Mass market advertising will yield some uptake and usage of H₂ vehicles. This will be achieved by utilising both traditional and social media advertising along with celebrity endorsement of H₂ vehicles. This strategy has seen particular success in the H₂ vehicles project in California, with higher rates of public acceptance of H₂ vehicle technology.</td>
</tr>
</tbody>
</table>

8.3 Timescale for Marketing

<table>
<thead>
<tr>
<th>TASK 1: Outreach &amp; Education</th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2013</td>
<td>2014</td>
<td>2015</td>
</tr>
<tr>
<td>1.1.1 Emergency Service Professionals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1.2 Safety Officers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1.3 State and Local Governments</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1.4 Business End Users</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1.5 General Public</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1.6 University Staff and Students</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1.7 School Teachers and Pupils</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TASK 2: Marketing and Advertising by Sector</th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2013</td>
<td>2014</td>
<td>2015</td>
</tr>
<tr>
<td>1.2.1 Brand and Marketing Material Development</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.2 Government</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.3 Young Adults (10-20 years)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.4 Adults (&gt;21 years)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.5 Business End Users</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.6 General Public</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The advertisement (original size 8” x 12”) to the left is an example of a possible advertisement of the hydrogen infrastructure.

The image was specifically chosen for the messages that it portrays that can be positively identified with Hydrogen, e.g., the vast expanses of greenery on the banks. In addition, it was felt that the stream, which starts clearly as water, looks like a sun bleached asphalt road in the distance due to the reflected clouds which can be easily associated to a transport network. The statement “No More Carbon... ...Just Water” was felt to be simple yet clearly explained one of the primary benefits of a hydrogen vehicle.

Branding of the Hydrogen Infrastructure will be paramount to its success. “The East Coast Hydrogen Highway” is quite a strong brand name for the setting up of the hydrogen infrastructure along the I95. It was also felt that the tagline “The Greener American Dream” would appeal to all different social groups of America.

1 Image source: [http://legarsraide.deviantart.com/art/Forest-water-highway-310185371](http://legarsraide.deviantart.com/art/Forest-water-highway-310185371) accessed 02/05/2013
9. Appendix

9.1 Phase 0 – Existing hydrogen refuelling stations (cont. page 14)

9.2 Phase I highlighted city locations (cont. page 16)

9.3 Phase II tier 2 additional maps (cont. page 18)
9.4 Phase II tier 3 and phase III tier 1 (cont. page 19)
### 9.5 Sample refuelling station database (cont. page)

<table>
<thead>
<tr>
<th>#</th>
<th>Location</th>
<th>Income % over $200,000</th>
<th>Pop density</th>
<th>Land cost (house value)</th>
<th>Plot size</th>
<th>Potential scope to retrofit</th>
<th>Traffic data (daily average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1601 Wisconsin Avenue Northwest, Washington, DC 20007</td>
<td>27</td>
<td>17000</td>
<td>980,00</td>
<td>Large</td>
<td>High</td>
<td>15,800</td>
</tr>
<tr>
<td>2</td>
<td>5001 Connecticut Avenue Northwest, Washington, DC 20008</td>
<td>31</td>
<td>20000</td>
<td>800,000</td>
<td>Large</td>
<td>Medium</td>
<td>42,300</td>
</tr>
<tr>
<td>3</td>
<td>4861 Massachusetts Avenue Northwest, Washington, DC 20016</td>
<td>40</td>
<td>13000</td>
<td>800,000</td>
<td>Medium</td>
<td>Low</td>
<td>19,100</td>
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<tr>
<td>4</td>
<td>2240 North Glebe Road, Arlington, VA 22207</td>
<td>36</td>
<td>3600</td>
<td>800,000</td>
<td>Large</td>
<td>High</td>
<td>36,000</td>
</tr>
<tr>
<td>5</td>
<td>3299 Wilson Boulevard, Arlington, VA 22201</td>
<td>20</td>
<td>17000</td>
<td>700,000</td>
<td>Large</td>
<td>High</td>
<td>17,000</td>
</tr>
<tr>
<td>6</td>
<td>823 Pennsylvania Avenue Southeast, Washington, DC 20003</td>
<td>17</td>
<td>15000</td>
<td>700,000</td>
<td>Medium</td>
<td>High</td>
<td>16,800</td>
</tr>
<tr>
<td>7</td>
<td>2600 14th Street Northwest, Washington, DC 20009</td>
<td>8</td>
<td>50000</td>
<td>500,000</td>
<td>Large</td>
<td>High</td>
<td>20,700</td>
</tr>
<tr>
<td>8</td>
<td>4060 S Four Mile Run Dr, Arlington, VA 22206</td>
<td>5</td>
<td>17000</td>
<td>400,000</td>
<td>Large</td>
<td>High</td>
<td>18,000</td>
</tr>
<tr>
<td>9</td>
<td>6257 Old Dominion Drive, McLean, VA 22101</td>
<td>30</td>
<td>3000</td>
<td>850,000</td>
<td>Medium</td>
<td>Medium</td>
<td>11,000</td>
</tr>
<tr>
<td>10</td>
<td>7100 Wisconsin Avenue, Bethesda, MD 20814</td>
<td>40</td>
<td>10000</td>
<td>900,000</td>
<td>Large</td>
<td>High</td>
<td>38,000</td>
</tr>
<tr>
<td>11</td>
<td>5501 South Dakota Avenue Northeast, Washington, DC 20011</td>
<td>3</td>
<td>14000</td>
<td>380,00</td>
<td>Medium</td>
<td>High</td>
<td>28,800</td>
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<tr>
<td>12</td>
<td>2230 New York Avenue Northeast, Washington, DC 2002</td>
<td>1</td>
<td>4000</td>
<td>300,000</td>
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<td>Medium</td>
<td>71,900</td>
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<td>2801 Alabama Avenue Southeast, Washington, DC 20020</td>
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<td>High</td>
<td>11,400</td>
</tr>
<tr>
<td>14</td>
<td>7980 Georgia Avenue, Silver Spring, MD 20910</td>
<td>18</td>
<td>10000</td>
<td>500,000</td>
<td>Large</td>
<td>High</td>
<td>33,000</td>
</tr>
<tr>
<td>15</td>
<td>6729 Goldsboro Road, Bethesda, MD 20817</td>
<td>40</td>
<td>5000</td>
<td>900,000</td>
<td>Small</td>
<td>Low</td>
<td>20,000</td>
</tr>
<tr>
<td>16</td>
<td>501 South Washington Street, Alexandria, VA 22314</td>
<td>25</td>
<td>10000</td>
<td>800,000</td>
<td>Medium</td>
<td>Small</td>
<td>31,000</td>
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<td>17</td>
<td>7110 Baltimore Avenue, College Park, MD 20740</td>
<td>10</td>
<td>8000</td>
<td>400,000</td>
<td>Medium</td>
<td>Medium</td>
<td>26,000</td>
</tr>
<tr>
<td>18</td>
<td>4501 Benning Road Northeast, Washington, DC 20019</td>
<td>0</td>
<td>14000</td>
<td>200,000</td>
<td>Medium</td>
<td>High</td>
<td>29,000</td>
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</table>
9.6 Overview of Hydrogen Production

<table>
<thead>
<tr>
<th></th>
<th>Address</th>
<th>Year</th>
<th>Capacity</th>
<th>Size</th>
<th>Grade</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>6519 Arlington Boulevard, Falls Church, VA 22042</td>
<td>12</td>
<td>6000</td>
<td>Large</td>
<td>High</td>
<td>36000</td>
</tr>
<tr>
<td>20</td>
<td>8124 Old Dominion Drive, McLean, VA 22102</td>
<td>28</td>
<td>2000</td>
<td>Large</td>
<td>High</td>
<td>11,000</td>
</tr>
<tr>
<td>21</td>
<td>2326 1st Ave, New York, NY 10035</td>
<td>4</td>
<td>161948</td>
<td>med/large</td>
<td>high</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>2040 Frederick Douglass Boulevard, New York, NY 10026</td>
<td>4</td>
<td>659400</td>
<td>medium</td>
<td>high</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>255 East 125th Street, New York, NY 10035</td>
<td>4</td>
<td>9466</td>
<td>large</td>
<td>high</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>1657 Jerome Avenue, Bronx, NY 10453</td>
<td>0</td>
<td>73869</td>
<td>medium</td>
<td>high</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>484 New Jersey 4, Englewood, NJ 07631</td>
<td>19</td>
<td>3562</td>
<td>Large (multiple)</td>
<td>high</td>
<td></td>
</tr>
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<td>26</td>
<td>4000 Major Deegan Expressway, Bronx, NY 10470</td>
<td>0</td>
<td>0</td>
<td>medium</td>
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</tbody>
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![Hydrogen Production Chart](chart.png)

- **Coal**
- **Biomass**
- **Electrolysis (renewable)**
- **Electrolysis (distributed grid)**
- **Electrolysis (central)**
- **SMR (distributed)**
- **SMR (central)**
10. References


26. HYDROGEN STUDENT DESIGN CONTEST 2011: RESIDENTIAL REFUELING STATION, UNIVERSITY OF WATERLOO. Fowler, Dr. Michael, et al., et al.

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